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Synergies between neutrino oscillation experiments: an 'adequate' configuration for LBNO

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Abstract: Determination of the neutrino mass hierarchy, octant of the mixing angle θ_{23} and the CP violating phase $\delta_{\rm CP}$ are the unsolved problems in neutrino oscillation physics today. In this paper our aim is to obtain the minimum exposure required for the proposed Long Baseline Neutrino Oscillation (LBNO) experiment to determine the above unknowns. We emphasize on the advantage of exploiting the synergies offered by the existing and upcoming long-baseline and atmospheric neutrino experiments in economising the LBNO configuration. In particular, we do a combined analysis for LBNO, T2K, NOνA and INO. We consider three prospective LBNO setups — CERN-Pyhäsalmi (2290 km), CERN-Slanic (1500 km) and CERN-Fréjus (130 km) and evaluate the adequate exposure required in each case. Our analysis shows that the exposure required from LBNO can be reduced considerably due to the synergies arising from the inclusion of the other experiments.

Keywords: Neutrino Physics, CP violation

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Contents

1 Introduction

The measurement of a non-zero θ_{13} by the reactor experiments Double Chooz [1], Daya bay [2] and RENO [3] is an important milestone in neutrino oscillation studies. Together these experiments have given a more than 10σ significance in favour of a non-zero θ_{13} [4–6]. Recently a 7.5σ signal for non-zero θ_{13} by observing the $\nu_\mu - \nu_e$ oscillation has been announced by the T2K experiment [7]. The best-fit value of $\sin^2 2\theta_{13}$ as obtained from the global fits is close to 0.1. The discovery of a non-zero θ_{13} sets the stage for the determination of the remaining unknown neutrino oscillation parameters, namely — the ordering of neutrino mass eigenstates or mass hierarchy, the octant of the atmospheric mixing angle θ_{23} and the leptonic CP phase $\delta_{\rm CP}$. This defines the road map for future programmes in neutrino oscillation physics.

The first set of information on these quantities is expected to come from the long-baseline (LBL) experiments T2K [8] and NOνA [9]. While T2K has already started operation and is giving results, NOνA is scheduled to start data taking from 2014. Several studies have been carried out, exploring the potential of these experiments for determination of mass hierarchy, octant and $\delta_{\rm CP}$ [10–17]. More recent studies in view of the measured value of θ_{13} can be seen in refs. [18–24]. The results obtained using the currently projected sensitivities for T2K and NOνA can be summarized as follows:

(i) Hierarchy can be determined at 95% C.L. from the combined results from T2K and NOνA for favourable values of $\delta_{\rm CP}$.

(ii) Octant can be determined at 95% C.L. by the T2K + NOνA combination as long as $|45^\circ - \theta_{23}| > 6^\circ$ irrespective of hierarchy and $\delta_{\rm CP}$.

(iii) Hint for a non-zero $\delta_{\rm CP}$ close to maximal CP violation can be obtained at 95% C.L. This however requires a prior knowledge of mass hierarchy and octant of θ_{23}.

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It was realized in [23] that although atmospheric neutrino experiments are insensitive to δ_{CP} themselves, they can play an important role in the detection of CP violation through their ability to determine mass hierarchy. The reason for hierarchy sensitivity of atmospheric neutrinos can be attributed to the large matter effects experienced by the neutrinos while passing through longer path lengths en route the detector [25–27]. The major future atmospheric neutrino projects are HyperKamiokande and MEMPHYS using water Čerenkov technology [28, 29], India-based Neutrino Observatory (INO) which will be using a magnetized iron calorimeter detector [30] and PINGU which is an upgraded version of the IceCube detector and will use Antarctic ice as detector material and strings of digital optical modules as the detector element [31]. Large volume liquid Argon detectors have also been proposed [32, 33]. The capabilities of these experiments have been investigated in detail in several recent papers, see for example refs. [34–40]. In particular, the synergy between the LBL experiments and INO for determination of mass hierarchy has been discussed in [34, 35], for octant determination has been explored in [22] and that for δ_{CP} has been studied in [23]. The reason for this synergy lies in the different baselines, neutrino energy, earth matter effects and source and detector characteristics involved in various long-baseline and atmospheric experiments. This leads to a different dependence of their oscillation probabilities on the parameters making their data complementary to each other, increasing the sensitivity. However from the results obtained in the above studies one concludes that even if the current LBL experiments T2K and NOνA join forces with INO (which has already been granted project approval [41]), a conclusive 5σ evidence for the unknown parameters would still require new experiments.

One of the promising proposals for an oscillation experiment beyond the current and upcoming ones, is the LAGUNA-LBNO project in Europe.[1] The source of neutrinos for this experiment is likely to be at CERN. Various potential sites for the detector have been identified by LAGUNA, including Boulby (U.K.), Canfranc (Spain), Fréjus (France), Pyhäsalmi (Finland), Slanic (Romania), SUNLAB (Poland) and Umbria (Italy) [43]. Previous studies have already shown that some of these potential experiments can have very good capability for measuring the unknown parameters [43–45]. However, the precise configuration of LBNO is currently being deliberated and it is desirable to adjudge the information that can be gleaned from the combination of current generation LBL+atmospheric experiments in the planning of this experiment. In this paper we embark on such an exercise. We consider the iron calorimeter (ICAL) detector proposed by the INO collaboration as the atmospheric detector in conjunction with the LBL experiments T2K and NOνA and determine the configuration for LBNO with 'adequate' exposure which can determine the unknown oscillation parameters. The 'adequate' configuration is defined as one with the minimal exposure which would give a 5σ discovery potential for hierarchy and octant and 3σ discovery potential for δ_{CP} in the most unfavourable case. This configuration can be viewed as the first step in a staged approach that has been advocated by previous studies [45].

The plan of this paper is as follows. In the next section we give the experimental specifications that we have used to simulate NOνA, T2K, INO and the proposed LBNO

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[1] The LBNE collaboration in US is also considering the same physics goals [33, 42].

experiment. We then discuss briefly the synergies between neutrino oscillation experiments. The next three sections thereafter are devoted to the analysis of the experimental reach of the combination of experiments for determining the mass hierarchy, octant of θ_{23} and CP violation respectively. Finally, we summarize our results.

2 Simulation details

In this paper, we have considered the contributions of NOνA, T2K, ICAL@INO and LBNO towards determining the mass hierarchy, octant of θ_{23} and CP violation. Simulations of all long-baseline experiments were carried out using the GLoBES package [46, 47] along with its auxiliary data files [48, 49]. Given below are the specifications of these experiments.

For NOνA and T2K, we have considered the standard detector and beam specifications used in ref. [19]. NOνA, with 7.3×10^{20} protons on target (pot) per year is assumed to run for 3 years each in neutrino and antineutrino mode. The neutrinos are detected at a 14 kt TASD detector placed 14 mrad off-axis, at a distance of 812 km from the NuMI source. We have used the new efficiencies and resolutions for NOνA which are optimized for the moderately large value of θ_{13} [19, 50]. For T2K, the current plan is to have a total of 7.8×10^{21} pot over the entire runtime of T2K. In our simulations, we have adjusted the runtime so as to get a total of $\sim 8 \times 10^{21}$ pot. In this work, we have assumed that T2K will run entirely with neutrinos. We have taken a baseline of 295 km and detector mass of 22.5 kt for this experiment. The relevant experimental specifications have been taken from refs. [8, 17, 51, 52].

The ICAL detector at the INO site in southern India is a 50 kt magnetized iron calorimeter, which will detect muon neutrino events with the capacity for charge detection provided by a magnetic field of about 1.3 tesla. Charge identification allows a separation of neutrino and antineutrino events, which is advantageous for mass hierarchy determination. The detector is under construction and is expected to start functioning within a projected time frame of about 5 years. We have considered a 10 year run for this atmospheric neutrino experiment, giving it a total exposure of 500 kt yr. The neutrino energy and angular resolution of the detector are taken to be $0.1\sqrt{E(\text{GeV})}$ and 10° respectively, while its efficiency is taken to be 85%. These effective resolutions and efficiencies give results comparable to those obtained through a full detector simulation [35].

Out of the various possible options for the LBNO experiment listed in the previous section, we consider the following three options that are prominent in the literature: CERN-Pyhäsalmi, CERN-Slanic and CERN-Fréjus.[2] The specifications that we have used in this work are listed below in table 1. We have used the superbeam fluxes from ref. [54]. We have explicitly taken into account the effect of wrong-sign contamination for these experiments. In particular, we find that the neutrino contamination in the antineutrino beam can have a significant effect on the event rates.

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[2] The three options shortlisted for LBNO are CERN-Pyhäsalmi, CERN-Umbria and CERN-Fréjus. However, we consider the CERN-Slanic option (1540 km baseline), because it lies in the range of baselines that are well suited for δ_{CP} studies [53]. Thus, the three setups analyzed in this paper cover the full range of baselines under consideration.

Detector site	Pyhäsalmi	Slanic	Fréjus
Baseline	2290 km	1540 km	130 km
Detector Type	LArTPC	LArTPC	Water Čerenkov
Proton energy	50 GeV	50 GeV	4.5 GeV
Resolutions, efficiencies	as in ref. [45]	as in ref. [45]	as in ref. [55]
Signal systematics	5%	5%	5%
Background systematics	5%	5%	10%

Table 1. Experimental characteristics of the LBNO options considered in this paper.

We have fixed the 'true' values of the parameters close to the values obtained from global fits of world neutrino data [4–6]. We have taken: $\sin^2\theta_{12} = 0.304$, $|\Delta_{31}| = 2.4 \times 10^{-3}\,\text{eV}^2$, $\Delta_{21} = 7.65 \times 10^{-5}\,\text{eV}^2$ and $\sin^2 2\theta_{13} = 0.1$. Three representative true values of θ_{23} have been considered — 39°, 45° and 51° (except in the case of octant determination where a wider range and more intermediate values have been included). The true value of δ_{CP} is varied in its entire allowed range. All our results are shown for both cases — normal hierarchy (NH): $m_1 < m_2 \ll m_3$ and inverted hierarchy (IH): $m_3 \ll m_1 \lesssim m_2$. The 'test' values of the parameters are allowed to vary in the following ranges — $\theta_{23} \in [35°, 55°]$, $\sin^2 2\theta_{13} \in [0.085, 0.115]$, $\delta_{\text{CP}} \in [0, 360°)$. The test hierarchy is also allowed to run over both possibilities. We have imposed a prior on the value of $\sin^2 2\theta_{13}$ with an error $\sigma(\sin^2 2\theta_{13}) = 0.005$, which is the expected precision on this parameter from the reactor neutrino experiments [56]. We have however not imposed any prior on the atmospheric parameters, instead allowing the ν_μ disappearance channels to restrict their range. In all our simulations, we have taken into account the three-flavour-corrected definitions of the atmospheric parameters [57–59].

In the following sections, we analyze the ability of the experiments NOνA, T2K, ICAL@INO and LBNO to collectively determine the neutrino mass hierarchy, octant of θ_{23} and detect CP violation. We demand that this combination of experiments determine the mass hierarchy and octant of θ_{23} with a statistical significance corresponding to $\chi^2 = 25$, and that CP violation be detected with $\chi^2 = 9$.[3]

The aim of this exercise is to determine the least exposure required from LBNO in order to fulfil the above demands. Therefore, we have plotted the sensitivity to hierarchy/octant/CP violation for various different exposures of LBNO, combined with NOνA, T2K and INO. From this, we estimate the adequate amount of exposure required by LBNO. We express the exposure in units of pot-kt. This is a product of three experimental quantities:

$$\text{exposure (pot-kt)} = \text{beam intensity (pot/yr)} \times \text{runtime (yr)} \times \text{detector mass (kt)}\ . \quad (2.1)$$

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[3] Conventionally, these values are taken to correspond to 5σ and 3σ, respectively. However, it was recently pointed out in refs. [60, 61] that for a binary question such as hierarchy, the relation between χ^2 and confidence levels is somewhat involved. For more recent discussions on statistical interpretation, see refs. [62–64].

Thus, a given value of exposure can be achieved experimentally by adjusting the intensity, runtime and detector mass. The advantage of using this measure is that while the physics goals are expressed in terms of simply one number (the exposure), the experimental implementation of this exposure can be attained by various combinations of beam, detector and runtime settings. For example, an exposure of 45×10^{21} pot-kt could be achieved with a 1.5×10^{21} pot/yr beam running for 3 years with a 10 kt detector or a 3×10^{21} pot/yr beam running for 3 years with a 5 kt detector. In the terminology used in this paper, the exposures given correspond to each mode (neutrino and antineutrino). Thus, a runtime of n years implies n years each in neutrino and antineutrino mode totalling to $2n$ years.

3 Synergies between oscillation experiments

Neutrino oscillation parameters are measured by observing events at a detector, and inferring the oscillation probability from them. In different experiments (and oscillation channels), neutrinos travel different distances and have different energies. Moreover, depending on the baseline, they experience matter effects to varying degrees. The energy spectrum of the events seen at the detector is also affected by the initial flux of neutrinos. As a result of these effects, the dependence of the event spectrum on the oscillation parameters can be different.

When we try to fit the events to a set of oscillation parameters, data from various experiments tend to choose slightly different best-fit points. This was demonstrated explicitly in the context of octant sensitivity in ref. [22]. In a combined fit, data from each experiment gives (in general) some χ^2 at the best-fit point of the other experiments. As a result, the net χ^2 of a combined analysis is greater than the sum of the individual minima. Therefore, we say that there is a synergy between various experiments. This is the very principle that leads to the lifting of parameter degeneracies using various experiments.

In the left(right) panel of figure 1, we have shown the hierarchy(octant) determination capability of various experiments separately (without including priors) as well as from their combined analysis (without and with priors) for true $\theta_{23} = 39°$. In the left(right) panel, for LBNO, we have used the 1540 km setup with an exposure of $22.5(82.5) \times 10^{21}$ pot-kt, and assuming NH(IH) to be the true hierarchy. It is clear to see that the combined χ^2 is much larger than the sum of the individual contributions. For hierarchy determination, the effect of synergy is more pronounced around $\delta_{\mathrm{CP}} = 90°$ where the effect of degeneracy is maximum. For more favourable values of δ_{CP}, the effect is milder. In the plot for octant sensitivity, we find that apart from the synergy between long-baseline and atmospheric neutrino experiments, there is a tremendous synergy between these and the reactor neutrino data. This is evident from the substantial effect of adding the θ_{13} prior. The synergy between experiments for octant sensitivity is discussed in detail in ref. [22]. The synergy between long-baseline and atmospheric neutrino experiments in detecting CP violation has been pointed out in ref. [23, 65].

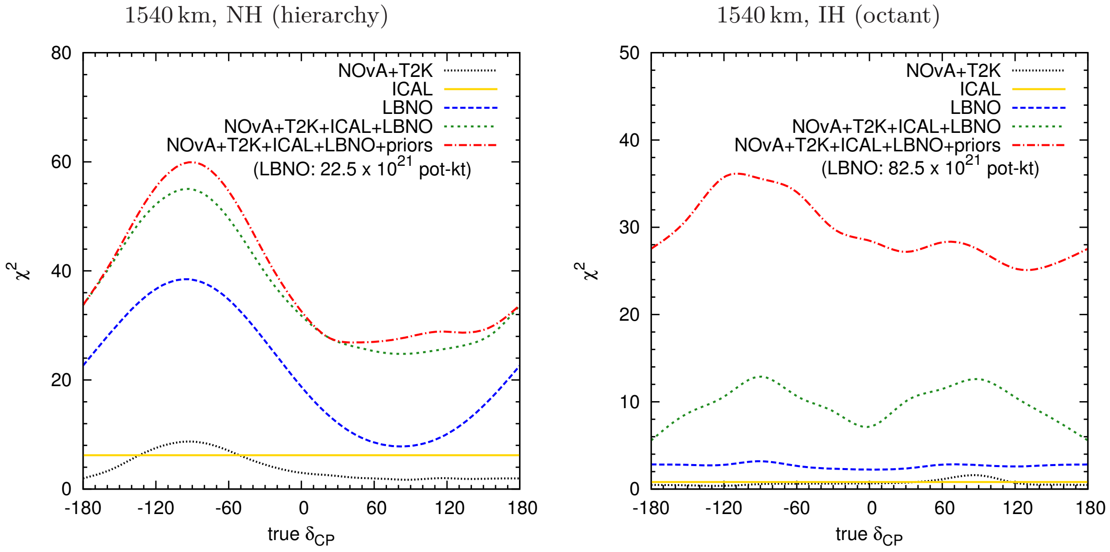


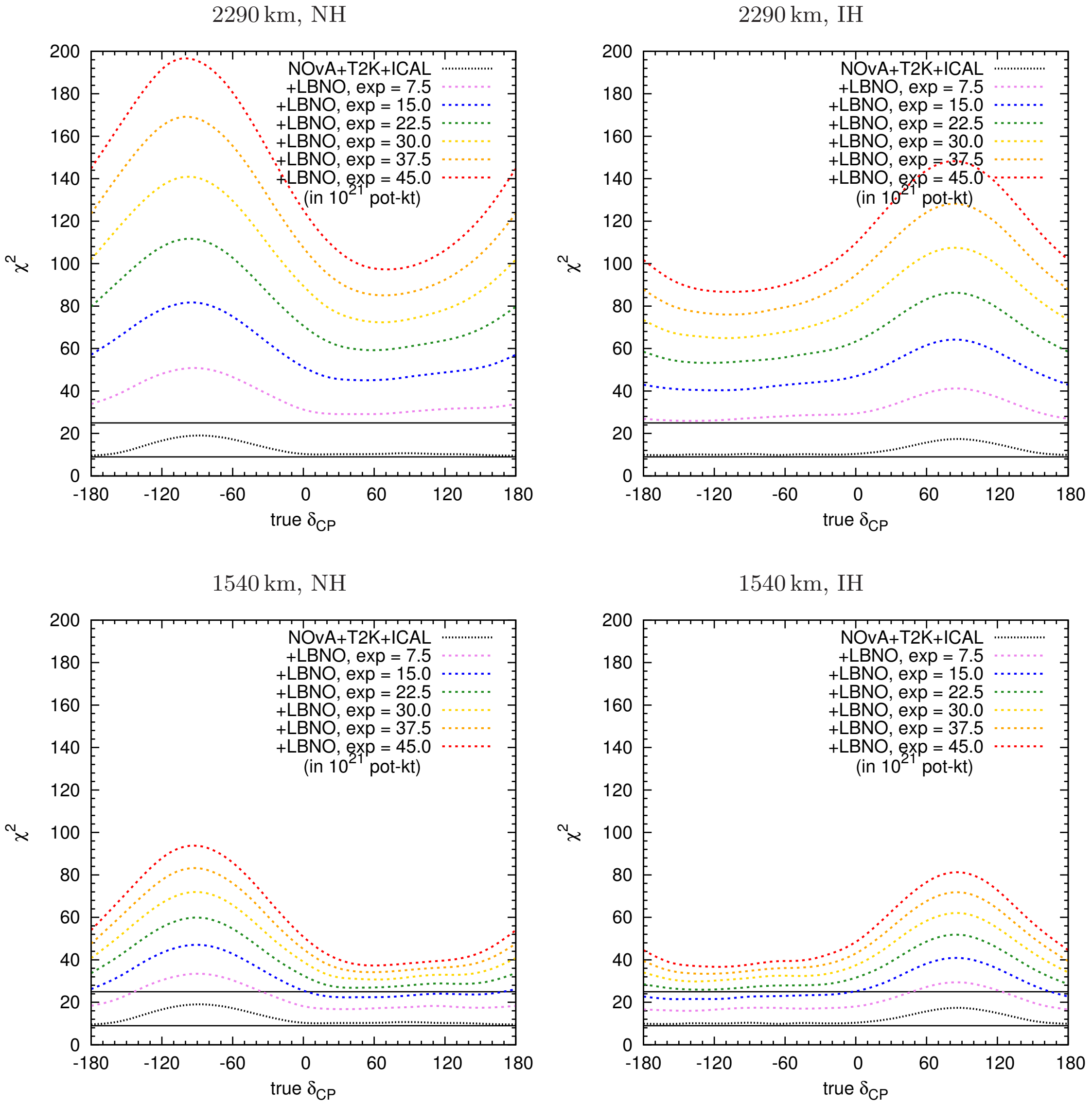
Figure 1. Demonstration of synergy between various oscillation experiments, by plotting hierarchy(octant) sensitivity χ^2 vs true $\delta_{\rm CP}$ in the left(right) panel. The curves are without priors unless specified. It is clear that the combined χ^2 is greater than the sum of individual χ^2 values.

4 Determination of mass hierarchy

Long-baseline experiments such as NOνA and T2K primarily use the $\nu_\mu \to \nu_e$ oscillation channel $P_{\mu e}$ to determine the neutrino mass hierarchy. Using the approximate perturbative formula for this probability [66–68], it can be seen that there is a hierarchy-$\delta_{\rm CP}$ degeneracy [69]. As a result, the hierarchy sensitivity of these experiments is a strong function of the value of $\delta_{\rm CP}$ in nature. In refs. [18, 69], it was shown that there exist favourable and unfavourable combinations of hierarchy and $\delta_{\rm CP}$ for the hierarchy sensitivity of LBL experiments. Combining information from NOνA and T2K improves the hierarchy sensitivity in the unfavourable part of the parameter space.

On the other hand, the hierarchy sensitivity of an atmospheric neutrino experiment like ICAL is almost independent of $\delta_{\rm CP}$. This is due to the effect of angular smearing that washes out the $\delta_{\rm CP}$-dependence [23]. Therefore, irrespective of the value of $\delta_{\rm CP}$ in nature, ICAL can determine the mass hierarchy. Thus combining ICAL results with that of T2K and NOνA is expected to give an enhanced sensitivity to mass hierarchy independently of the value of $\delta_{\rm CP}$ [34, 35].

Among the three chosen prospective baselines for LBNO, the 130 km setup has the lowest hierarchy sensitivity due to small matter effects. As the baseline increases, the hierarchy sensitivity becomes better because of enhanced matter effects. In particular, the 2290 km setup has the unique advantage of being close to satisfying the bimagic conditions [70–72]. This feature makes the baseline particularly suited for hierarchy determination. The above features are reflected in figure 2. In each of the panels of figure 2, the lowermost densely-dotted (black) curve shows the hierarchy sensitivity of the combination NOνA+T2K+ICAL. We see that these experiments can collectively give $\chi^2 \approx 9$ sensitivity


2290 km, NH

2290 km, IH

1540 km, NH

1540 km, IH

Figure 2. Hierarchy sensitivity χ^2 vs true δ_{CP}. The top(bottom) panels are for the 2290(1540) km baseline. The left(right) panels are for true NH(IH). In all the panels, the lowermost densely-dotted (black) curve is for NOνA+T2K+ICAL, while the curves above are for NOνA+T2K+ICAL+LBNO, for various values of LBNO exposure. All the plotted sensitivities are for the least favourable value of true θ_{23}.

to the hierarchy. Therefore, in keeping with our aims, we need to determine the minimum exposure for LBNO, such that the combination NOνA+T2K+ICAL+LBNO crosses the threshold of $\chi^2 = 25$ for all values of δ_{CP}. For this, we have plotted the combined sensitivity of NOνA+T2K+ICAL+LBNO for various values of LBNO exposure (in units of 10^{21} pot-kt). The results are shown for two baselines — 2290 km and 1540 km, and for both hierarchies. We find that our results are consistent with those shown in ref. [44], for the same beam power and oscillation parameters. For the baseline of 130 km, it is not possible

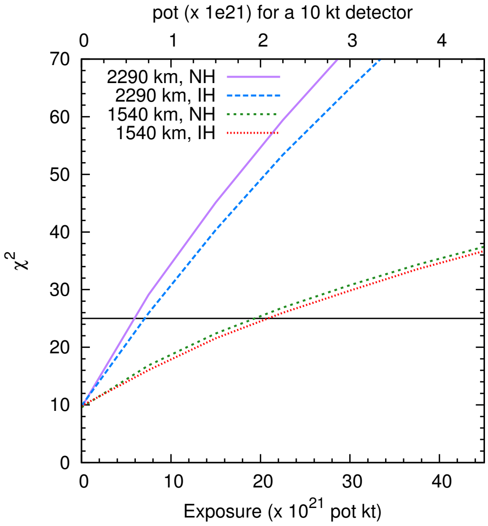


Figure 3. Hierarchy sensitivity χ^2 vs LBNO exposure, for both baselines and hierarchies under consideration. The value of exposure shown here is adequate to exclude the wrong hierarchy for all values of $\delta_{\rm CP}$. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 kt.

to cross $\chi^2 = 25$ even with extremely high exposure. Therefore we have not shown the corresponding plots for this baseline. We considered three true values of θ_{23} — $39°, 45°, 51°$ and chose the least favourable of these in generating the figures. Thus, our results represent the most conservative case. We find that in most cases, the minimum χ^2 for hierarchy determination occurs for true $\theta_{23} = 39°$.

Finally, in figure 3, we have condensed all this information into a single plot. We have shown the sensitivity for the experiments as a function of the LBNO exposure. We see that for 2290(1540) km, it is sufficient for LBNO to have an exposure of around $7\times10^{21}(21\times10^{21})$ pot-kt in order to get $\chi^2 = 25$ sensitivity for all values of $\delta_{\rm CP}$. Along the upper edge of the graph, we have provided an additional axis, which denotes the total pot required if we assume that the detector has a mass of 10 kt. For 2290(1540) km, we need a total of $0.7 \times 10^{21}(2.1 \times 10^{21})$ pot. To get some idea of the time scale involved we consider for instance the beam intensity used in ref. [45] which corresponds to 3×10^{21} pot/yr delivered by a 50 GeV proton beam from CERN with beam power 1.6 MW. The total pot of 0.7×10^{21} for a 10 kt detector at the 2290 (1540) km baseline would thus need less than 1(2) years (total, inclusive of ν and $\overline{\nu}$ runs) to establish mass hierarchy with $\chi^2 = 25$.

Figure 4, demonstrates the synergy between long-baseline and atmospheric neutrino experiments. We have chosen the 2290(1540) km baseline as an illustrative case in the left(right) panels, with the true hierarchy assumed to be IH. The densely-dotted (black) curve at the bottom shows the hierarchy sensitivity of NOνA+T2K without any atmospheric neutrino data included in the analysis. If the atmospheric information is not included then the combination of NOνA+T2K+LBNO would need about 11×10^{21} pot-kt in order to attain $\chi^2 = 25$, for the 2290 baseline. Assuming a beam intensity of 3×10^{21} pot/yr

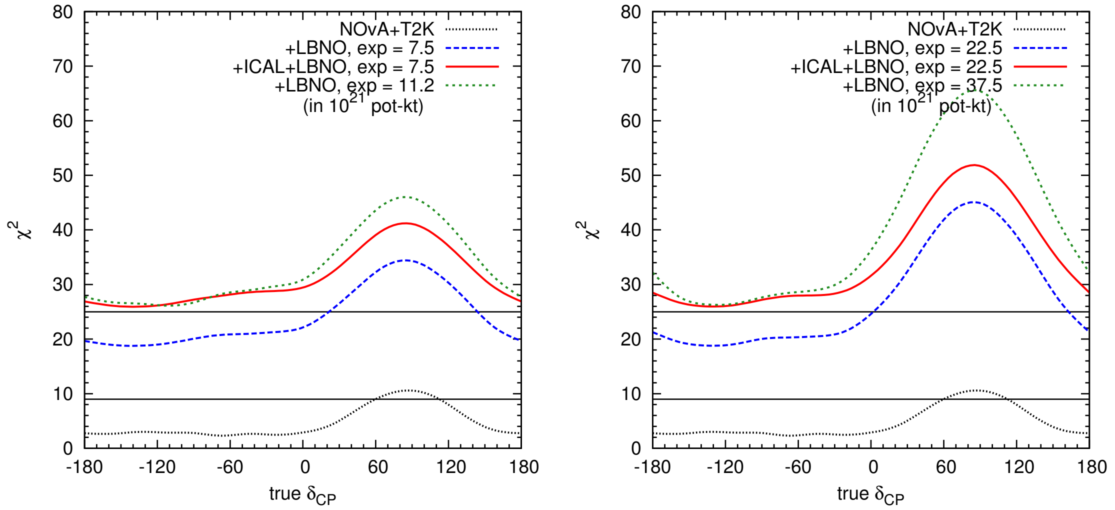


Figure 4. Hierarchy sensitivity χ^2 for different combinations of experiments, demonstrating the synergy between them. The left(right) panel is for a LBNO baseline of 2290(1540) km, assuming IH to be true. With only T2K+NOνA+LBNO (dashed, blue), the sensitivity is lower than for T2K+NOνA+LBNO+ICAL (red, solid). Without ICAL data, the LBNO exposure would have to be increased substantially (dotted, green) in order to get comparable sensitivity. All the plotted sensitivities are for the least favourable value of true θ_{23}.

this would require less than a year to measure the hierarchy with a 10 kt detector. Combining these with ICAL reduces the exposure to 7×10^{21} pot-kt. Thus, for the same beam intensity one can achieve the same sensitivity with a 7 kt detector. Similar conclusions can be drawn for the 1540 km set-up. It should be noted that the numbers in figure 4 are sample values at which the simulations are performed. The exposure required for each set-up to attain the 'adequate' values can be read off from figure 3 and is presented in table 2.

5 Determination of octant of θ_{23}

The octant sensitivity of long-baseline experiments has been studied in detail recently, both alone [20, 73] and in conjunction with atmospheric neutrino experiments [22]. As in the case of hierarchy, adding information from various experiments enhances the sensitivity. However, it is the precise knowledge of the value of θ_{13} that plays a crucial role in determining the octant correctly. In figure 5, the lowermost densely-dotted (black) curve denotes the ability of NOνA+T2K+ICAL to determine the octant as a function of the true value of θ_{23} in nature. Again, the other curves denote the combined sensitivity of NOνA+T2K+ICAL+LBNO for various values of LBNO exposure (in units of 10^{21} pot-kt). We generated the results for various true values of δ_{CP}, and the results shown in the figure are for the most conservative case. We see that only with NOνA+T2K+ICAL, the octant can be determined at $> 3\sigma$ C.L. when $\theta_{23} = 39°$. For values closer to 45°, the sensitivity gets steadily worse. The addition of LBNO data increases the sensitivity. For the range of

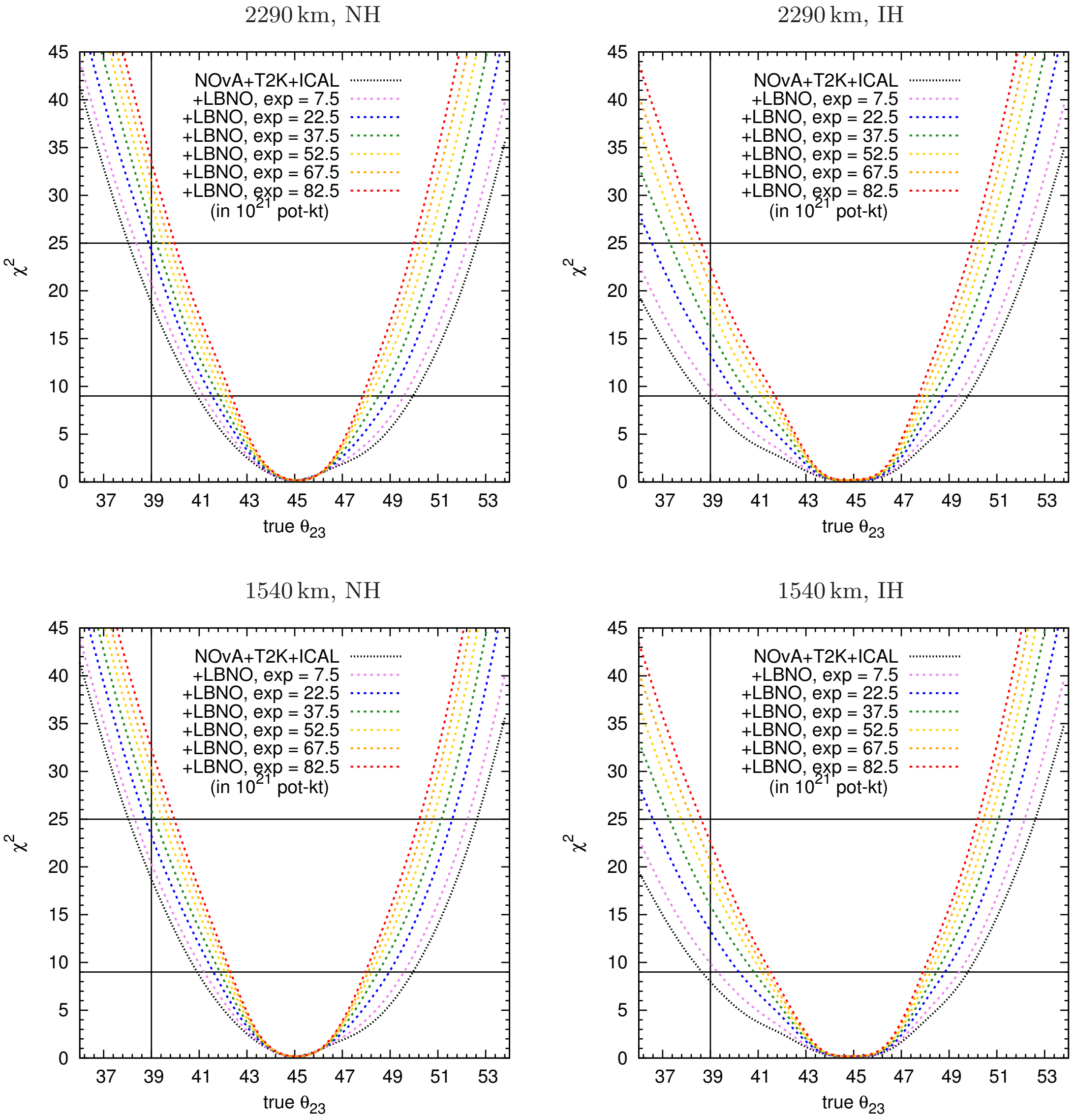


Figure 5. Octant sensitivity χ^2 vs true θ_{23}. The top(bottom) panels are for the 2290(1540) km baseline. The left(right) panels are for true NH(IH). In all the panels, the lowermost densely-dotted (black) curve is for NOνA+T2K+ICAL, while the curves above are for NOνA+T2K+ICAL+LBNO, for various values of LBNO exposure. All the plotted sensitivities are for the least favourable value of true δ_{CP}.

exposures considered, it is possible to get a $\chi^2 = 25$ sensitivity to the octant as long as θ_{23} deviates from maximality by at least $\sim 6°$.

In figure 6, we have shown how the octant sensitivity of these experiments increases as the exposure for LBNO is increased. For this, we have chosen the true value of θ_{23} to be 39°. Because of the better performance of NOνA+T2K+ICAL when NH is true, the adequate exposure for LBNO is higher when IH is true. Given our current state of ignorance about the true hierarchy in nature, we list here the higher of the two numbers. It is sufficient

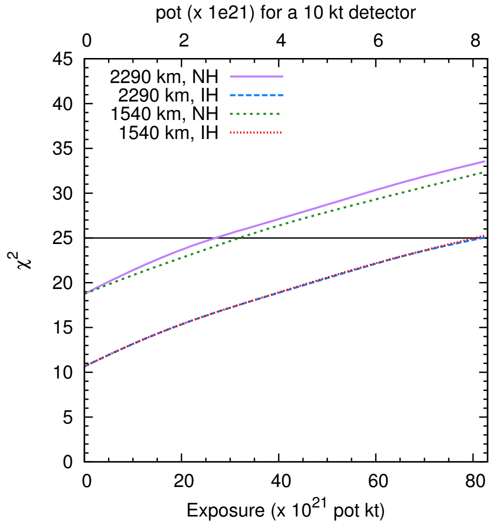


Figure 6. Octant sensitivity χ^2 vs LBNO exposure, for the 2290 km and 1540 km baselines and both hierarchies, with $\theta_{23} = 39°$. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 kt.

to have an exposure of around 83×10^{21} pot-kt to reach $\chi^2 = 25$ with both the baselines. The upper axis shows the total pot required, with a 10 kt detector. For instance, we see that 8.3×10^{21} pot is sufficient if we have a 10 kt detector. This translates to a runtime of a little under 3 years in each ν and $\overline{\nu}$ mode, given an intensity of 3×10^{21} pot/yr.

Figure 7 is the same as figure 5, but for the 130 km baseline. As expected, because of smaller matter effects, the exposure required to determine the octant is much higher than for the other two baselines. However, for a large mass detector like MEMPHYS that is being planned for the Fréjus site, this exposure is not difficult to attain. The sensitivity as a function of LBNO exposure for this baseline is shown in figure 8. We need an exposure of around 400×10^{21} pot-kt in this case. For this graph, the upper axis shows the required pot if we consider a 500 kt detector, as proposed for MEMPHYS [55]. We see that for such a large mass detector, only around 0.8×10^{21} pot is adequate to exclude the octant for $\theta_{23} = 39°$. Thus the beam intensity in pot is better than the other two set-ups.

Figure 9 shows the synergy between LBL experiments and ICAL. In the left(right) panel, we have chosen the LBNO baseline of 2290(1540) km to illustrate this point. IH is assumed to be the true hierarchy. The sensitivity of T2K+NOνA alone (densely-dotted, black curve) is enhanced by adding data from ICAL and LBNO. The solid (red) curve in the left panel shows that an exposure of 82.5×10^{21} pot-kt is enough to determine the octant with $\chi^2 = 25$ at 39°. But without ICAL data (dashed, blue curve), the sensitivity would be lower. The dotted (green) curve shows that only with 112.5×10^{21} pot-kt (more than 35% higher than the adequate amount), can we attain $\chi^2 = 25$ without ICAL. For 1540 km (right panel) also, similar features are observed. This demonstrates the advantage of adding atmospheric neutrino data.

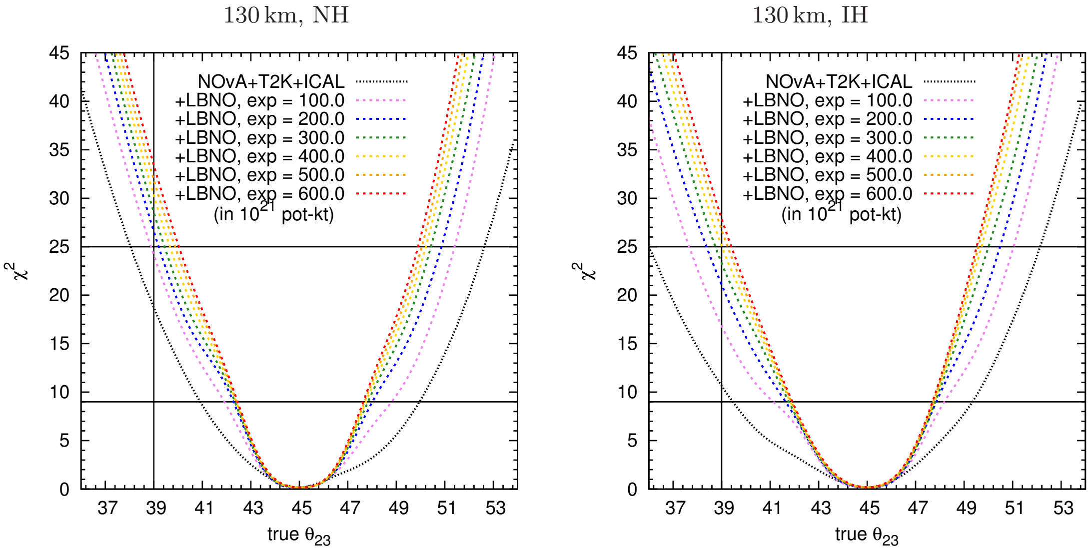


Figure 7. Octant sensitivity χ^2 vs true θ_{23} for the 130 km baseline. The left(right) panel is for true NH(IH). In both panels, the lowermost densely-dotted (black) curve is for NOνA+T2K+ICAL, while the curves above are for NOνA+T2K+ICAL+LBNO, for various values of LBNO exposure. All the plotted sensitivities are for the least favourable value of true δ_{CP}.

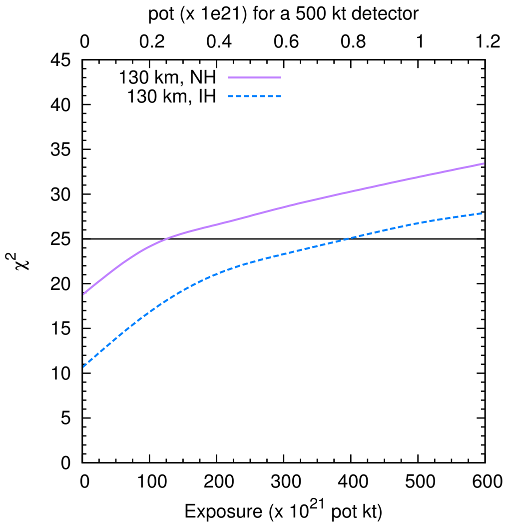


Figure 8. Octant sensitivity χ^2 vs LBNO exposure, for the 130 km baseline and both hierarchies, with $\theta_{23} = 39°$. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 500 kt.

6 Evidence for CP violation

Measurement of δ_{CP} is one of the most challenging problems in neutrino physics today. For the moderately large value of θ_{13} measured by the reactor neutrino experiments, it is possible for NOνA and T2K to provide some hint on this parameter. In this paper, we discuss the detection of CP violation, i.e. the ability of an experiment to exclude the cases

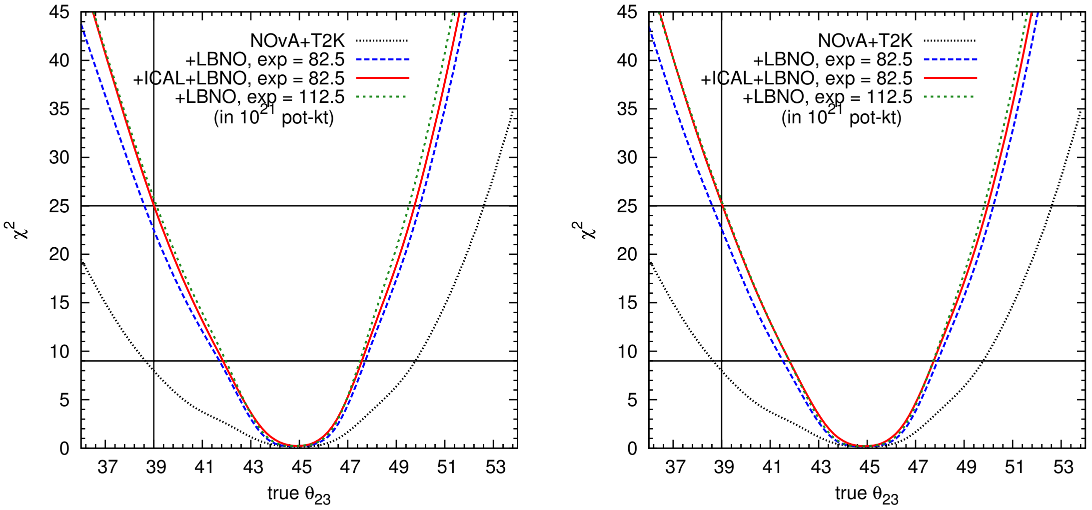


Figure 9. Octant sensitivity χ^2 for different combinations of experiments, demonstrating the synergy between them. The left(right) panel is for a LBNO baseline of 2290(1540) km, assuming IH to be true. With only T2K+NOνA+LBNO (dashed, blue), the sensitivity is lower than for T2K+NOνA+LBNO+ICAL (red, solid). Without ICAL data, the LBNO exposure would have to be increased substantially (dotted, green) in order to get comparable sensitivity. All the plotted sensitivities are for the least favourable value of true $\delta_{\rm CP}$.

$\delta_{\rm CP} = 0$ or 180°.[4] We show our results as a function of $\delta_{\rm CP}$ in figure 10. Like in the case of hierarchy exclusion, we have minimized over three different true values of θ_{23}, thus choosing the most conservative case possible. NOνA and T2K suffer from the hierarchy-$\delta_{\rm CP}$ degeneracy, because of which their CP detection potential is compromised for unfavourable values of $\delta_{\rm CP}$. This degeneracy can be lifted by including information from ICAL, which excludes the wrong hierarchy solution [23]. Thus, in spite of not having any intrinsic $\delta_{\rm CP}$ sensitivity, addition of atmospheric neutrino data improves the CP sensitivity of LBL experiments, provided the experiment itself does not have sufficient hierarchy sensitivity.

We see in figure 10 that with NOνA+T2K+ICAL, only around $\chi^2 = 4$ can be attained, for a small range of $\delta_{\rm CP}$ values around ±90°. Adding LBNO data with increasing exposure can enhance this, and even help to achieve $\chi^2 = 9$ CP detection for some range of $\delta_{\rm CP}$. In figure 11, we have plotted the fraction of $\delta_{\rm CP}$ for which CP violation can be detected with $\chi^2 = 9$, as a function of the LBNO exposure. As an example, if we aim to detect CP violation for at least 20% of $\delta_{\rm CP}$ values, then we require around $240 \times 10^{21}(170 \times 10^{21})$ pot-kt exposure from LBNO with a baseline of 2290(1540) km. It can also be seen from the figure that with 350×10^{21} pot-kt exposure, the maximum CP fraction for which a 3σ sensitivity is achievable ranges from 30% to 40%. The upper axis shows that these values correspond to $24 \times 10^{21}(17 \times 10^{21})$ pot, if we consider a 10 kt detector.

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[4] We emphasize that by 'CP violation detection', we mean evidence that CP is violated in the neutrino sector. This is usually referred to in the literature as 'CP violation discovery'. In this paper, we have avoided using this standard terminology, since the word 'discovery' is usually taken to mean 5σ significance.

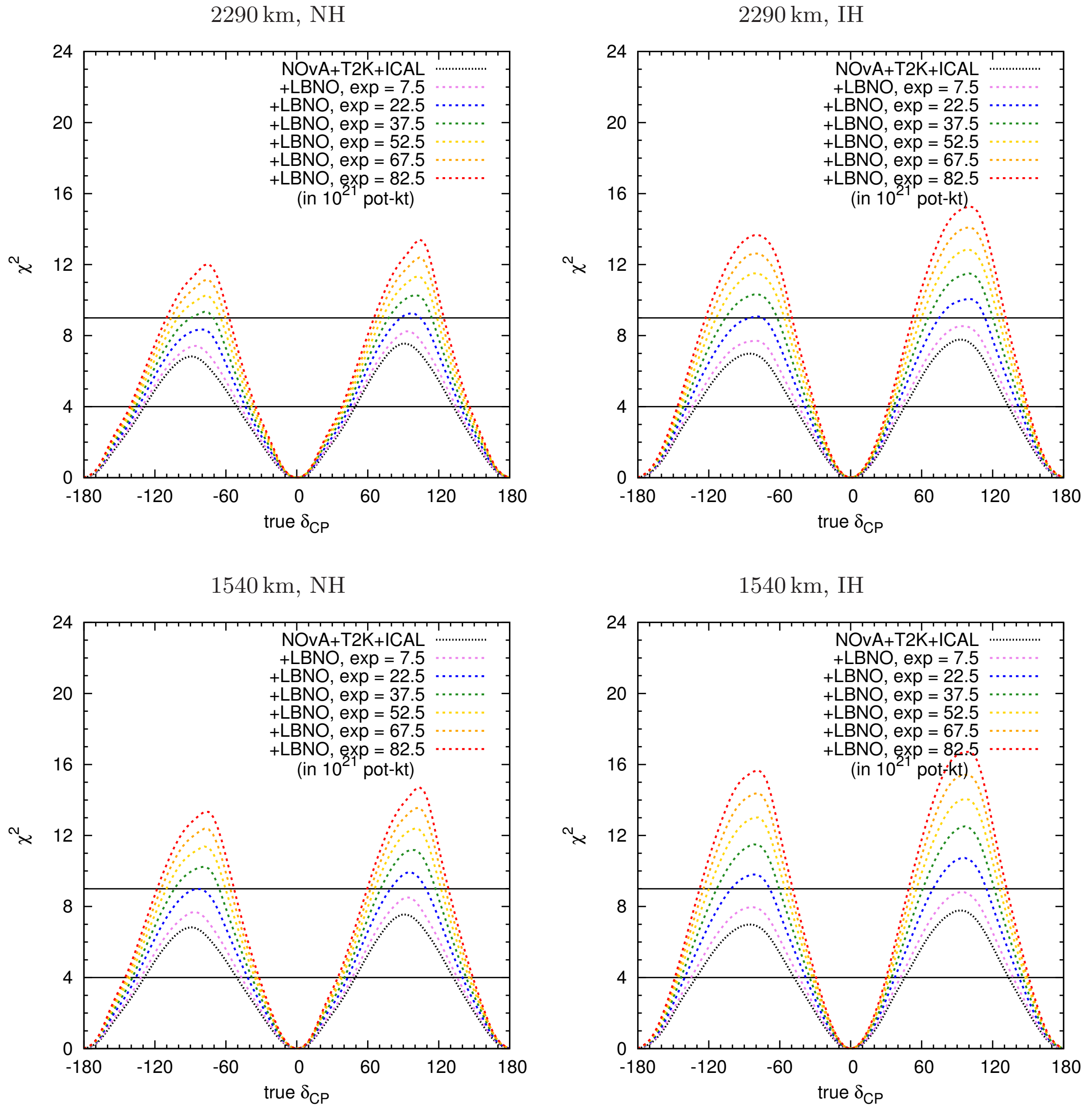

Figure 10. CP violation detection χ^2 vs true $\delta_{\rm CP}$. The top(bottom) panels are for the 2290(1540) km baseline. The left(right) panels are for true NH(IH). In all the panels, the lowermost densely-dotted (black) curve is for NOνA+T2K+ICAL, while the curves above are for NOνA+T2K+ICAL+LBNO, for various values of LBNO exposure. All the plotted sensitivities are for the least favourable value of true θ_{23}.

Figures 12 and 13 show the results for the 130 km option. Once again, we see that an exposure much higher than the longer baselines is required. In this case, CP detection for 20% $\delta_{\rm CP}$ values requires an exposure of around 35×10^{21} pot-kt. This is not difficult to achieve with a large MEMPHYS-like detector. In fact, the total pot required by a 500 kt detector at 130 km is only around 0.07×10^{21} pot. Moreover, an underground megaton scale detector like MEMPHYS can also be used to collect atmospheric neutrino data, which will further enhance the sensitivity [29].

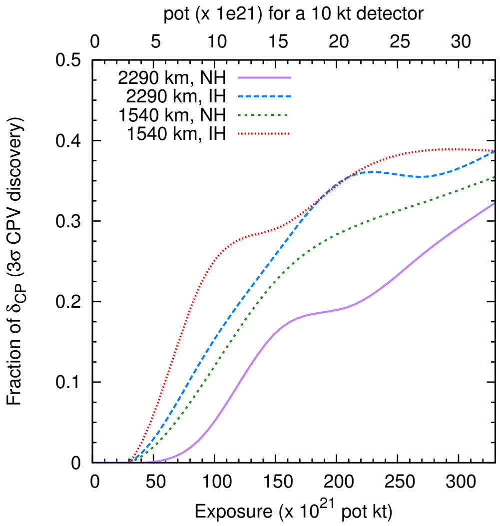

Figure 11. Fraction of the full δ_{CP} range for which it is possible to detect CP violation (exclude $\delta_{\mathrm{CP}} = 0, 180°$) at 3σ vs LBNO exposure, for the 2290 km and 1540 km baselines and both hierarchies. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 kt.

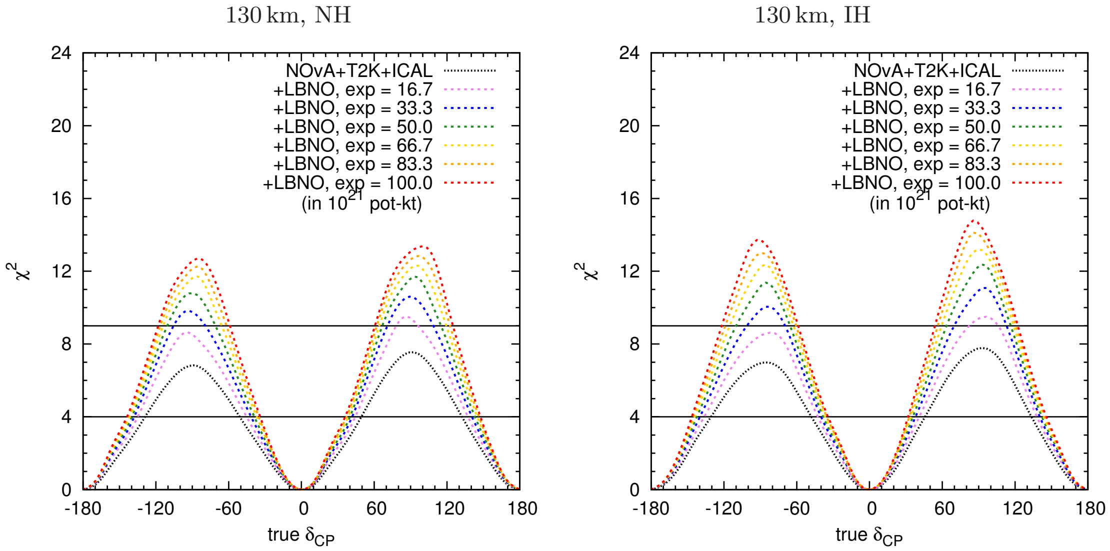

Figure 12. CP violation detection χ^2 vs true δ_{CP} for the 130 km baseline. The left(right) panel is for true NH(IH). In both panels, the lowermost densely-dotted (black) curve is for NOνA+T2K+ICAL, while the curves above are for NOνA+T2K+ICAL+LBNO, for various values of LBNO exposure. All the plotted sensitivities are for the least favourable value of true θ_{23}.

In figure 14, we have demonstrated the synergy between atmospheric and long-baseline experiments for the baseline of 130 km and with NH. We see that with only T2K+NOνA (densely-dotted, black curve), we suffer from the hierarchy-δ_{CP} degeneracy in the unfavourable region of δ_{CP}. This degeneracy is lifted by adding information from other

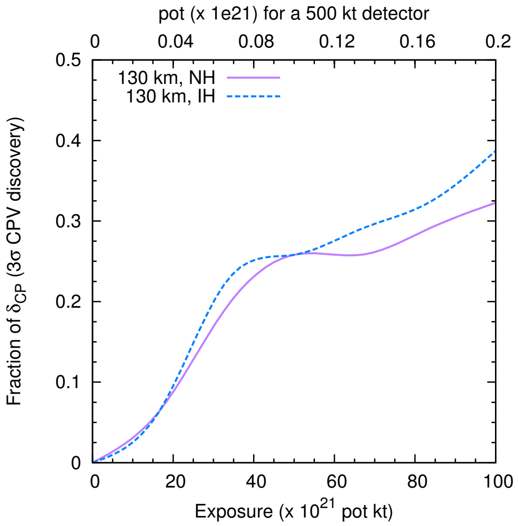

Figure 13. Fraction of the full $\delta_{\rm CP}$ range for which it is possible to detect CP violation (exclude $\delta_{\rm CP} = 0, 180°$) at 3σ vs LBNO exposure, for the 130 km baseline and both hierarchies. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 500 kt.

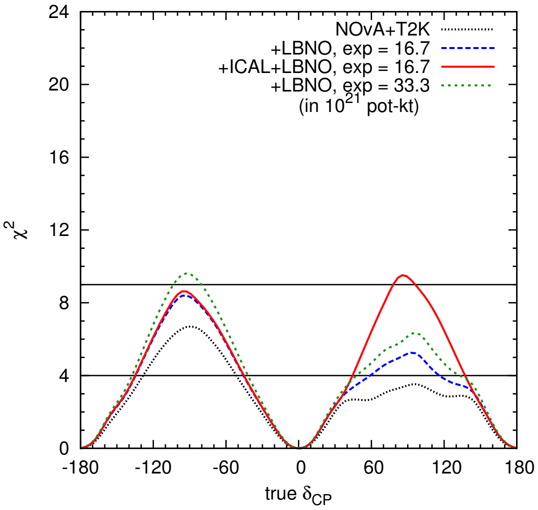

Figure 14. CP detection sensitivity χ^2 for different combinations of experiments, demonstrating the synergy between them. This plot is for a LBNO baseline of 130 km, assuming NH to be true. With only T2K+NOνA+LBNO (dashed, blue), the sensitivity is lower than for T2K+NOνA+LBNO+ICAL (red, solid). Without ICAL data, the LBNO exposure would have to be increased substantially (dotted, green) in order to get comparable sensitivity. All the plotted sensitivities are for the least favourable value of true θ_{23}.

experiments. On adding data from ICAL and 16.7×10^{21} pot-kt of LBNO (solid, red curve), we just reach $\chi^2 = 9$ sensitivity. With the same LBNO exposure, absence of ICAL data reduces the detection reach, as seen from the dashed (blue) curve. Reaching $\chi^2 = 9$

	adequate exposure (pot-kt) for		
	2290 km	1540 km	130 km
Hierarchy exclusion ($\chi^2 = 25$)	$7(11) \times 10^{21}$	$21(37) \times 10^{21}$	–
Octant exclusion at 39° ($\chi^2 = 25$)	$83(113) \times 10^{21}$	$83(113) \times 10^{21}$	$400(600) \times 10^{21}$
CP violation detection ($\chi^2 = 9$) for 20% fraction of $\delta_{\rm CP}$	$240(240) \times 10^{21}$	$170(170) \times 10^{21}$	$35(100) \times 10^{21}$

Table 2. Summary of results: 'adequate' exposure in pot-kt for three LBNO configurations to achieve the physics goals. The numbers given in parentheses indicate the required exposure if atmospheric neutrino data from ICAL is not included.

without ICAL will require the LBNO exposure to be doubled, as the dotted (green) curve shows. Thus, in spite of not having much intrinsic CP sensitivity, ICAL data contributes substantially towards CP sensitivity. For the two longer baselines, LBNO even with very low exposure in conjunction with T2K and NOνA can break the hierarchy-$\delta_{\rm CP}$ degeneracy by excluding the wrong hierarchy solution. Therefore, the contribution of ICAL towards detecting CP violation becomes redundant in this case.

7 Conclusion

The reactor neutrino experiments have measured the value of θ_{13} to be moderately large. This is expected to facilitate the determination of the three unknowns in neutrino oscillation studies — the mass hierarchy, octant of θ_{23} and $\delta_{\rm CP}$. However the current LBL experiments T2K and NOνA have limited sensitivity to these parameters even for such large values of θ_{13}. Combining the data from these experiments with atmospheric neutrino data can result in an enhanced sensitivity due to the synergistic aspects amongst them. However a conclusive 5σ evidence would still be difficult to achieve and many future proposals are being discussed for realizing this.

One of the most propitious among these is the LBNO project in Europe. The exact design and baseline for this is still under consideration. In this paper we have explored the minimum exposure needed for such a set-up and quantified the 'adequate' configuration that can exclude the wrong hierarchy ($\chi^2 = 25$), exclude the wrong octant ($\chi^2 = 25$) and detect CP violation ($\chi^2 = 9$). We have determined the adequate exposure required for LBNO in units of pot-kt and for the least favourable true hierarchy, θ_{23} and $\delta_{\rm CP}$. In determining the requisite exposure we fully exploit the possible synergies between the existing LBL experiment T2K, the upcoming LBL experiment NOνA and the atmospheric neutrino experiment ICAL@INO which is likely to commence data taking in five years time. For the prospective LBNO configuration we consider three options: CERN-Pyhäsalmi (2290 km) baseline with a LArTPC, CERN-Slanic (1500 km) with a LArTPC and CERN-Fréjus (130 km) with a Water Čerenkov detector. The 'adequate' exposure needed is summarized in table 2 where we give the results for T2K+NOνA+LBNO with and without ICAL. Inclusion of the atmospheric data from ICAL can play a significant role in reducing the exposure required for hierarchy and octant determination for the 2290 and 1540 km set-ups and for octant and CP detection for the 130 km set up.

Of the two longer baselines, we find that 2290 km is best suited to determine the mass hierarchy, while 1540 km is better for detecting CP violation. However, 130 km is the best candidate for CP violation physics. The 'adequate' exposures listed in this work can be attained by various combinations of beam power, runtime and detector mass. These minimal values can be used to set up the first phase of LBNO, if an incremental/staged approach is being followed. Finally, we would like to emphasize that the synergies between the existing and upcoming LBL and atmospheric experiments can play an important role and should be taken into consideration in planning economised future facilities.

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